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Yield Pillar Sizing: An Empirical Approach

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

U.S. Department of the Interior
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With an Appendix on the Pillar Size program by Alan D. Rock

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

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Rhea Lydia Graham, Director

This report has been technically reviewed, but it has not been copy edited because of the closure of the agency.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot
m	meter
MPa	megapascal
psi	pound per square inch

DISCLAIMER OF LIABILITY

YIELD PILLAR SIZING: AN EMPIRICAL APPROACH

By Richard O. Kneisley[1]

With an Appendix on the Pillar Size program by Alan D. Rock

ABSTRACT

An empirical method, based on U. S. Bureau of Mines field studies in several Western U.S. coal mines, is presented for sizing gate road yield pillars. Discriminant analysis was used to generate functions separating successful from unsuccessful case studies. These functions relate the pillar width-height and extraction ratios and a pillar development factor to the Coal Mine Roof Rating System (CMRR), and are assumed to establish three criteria that other entry systems, under similar conditions, must satisfy. A program, Pillar Sizer, from user-provided inputs, generates a range of pillar sizes that meets the proposed criteria. Although the analysis is based on a sample consisting primarily of two-entry systems, the derived expressions generate pillar sizes closely agreeing with observed, two-entry and three-entry in situ pillars. It is concluded that the proposed approach should assist mine operators estimate entry system yield pillar dimensions.

INTRODUCTION

This research was conducted as part of an ongoing U.S. Bureau of Mines (USBM) study to develop a comprehensive design methodology for yielding gate road systems. Longwall mining using two-entry yield pillar gate roads was first introduced at the Sunnyside Mines, Sunnyside, UT, to combat the occurrence of severe bumps that had rendered previously successful, multiseam room-and-pillar mining impractical (*1-4*).[2] Two-entry yielding pillar systems are generally employed in deep Western U.S. mines to mitigate coal bumps and reduce high stresses. Other applications include controlling floor heave and cutter roof (*5*).

Unlike full-support abutment pillars, yielding pillars are "sized" to crush out in a gradual, controlled manner. As these pillars yield and the adjacent strata deflect, a reduced stress zone forms. Pillar softening and the resulting separation of the immediate strata from the rock mass transfer high stresses onto adjacent mine

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[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

structures. Although yield pillar behavior is conceptually simple, in-mine implementation is often difficult. These difficulties arise, in part, from—

1. A lack of one universally accepted yield pillar system design method;
2. Misapplication of a successful design at operation(s) having possibly different conditions;
3. Attempted usage under possibly inappropriate conditions, for example, under weak roof conditions or at insufficient depth to induce pillar yielding (*5*).

Yield pillar "design" methods range from analytical approaches and numerical modeling simulations to reliance upon trial-and-error solutions developed for site-specific conditions (*6-12*). Several analytical pillar design methods, most based on modifications to the confined core approach, have been proposed for sizing yielding pillars (*6-8,11-12*). Essentially, these methods determine the depth into the rib that coal failure extends. Field studies have measured yield zone extents that agree with those predicted by analytical methods (*13-14*). The *maximum* yield pillar width should not exceed twice the extent of the failed coal zone. Although having greatly advanced the knowledge of pillar mechanics, these methods are, in many cases, complex and often highly sensitive to poorly known and/or difficult to measure variables such as, the postfailure strengths and deformation behavior of failed coal, and properties of the coal-host rock interfaces. From a more practical standpoint, even though some of these techniques include the entries for determining pillar loads and/or stress distributions, entry stability is not included.

This report presents an empirically based method for sizing yield pillars. The approach is based on a statistical analysis from available Western U.S. longwall case studies. The proposed method, although empirical in nature, includes factors that are mechanics-based, an attempt to provide a middle ground between the more complex theoretical methods and trial-and-error solutions.

BACKGROUND

The proposed pillar-sizing method attempts to quantify yielding pillar entry system requirements, defined qualitatively by DeMarco (*5*), using statistical methods included in the ALPS-CMRR technique (*15-16*), the successful and widely used method for sizing abutment pillar systems. DeMarco (*5*) lists the following requirements for a successful yielding pillar gate road:

1. That sufficient depth exists to initiate pillar yielding;
2. That the mine roof be of sufficient quality to withstand the deformation resulting from pillar yielding;
3. That sufficient floor quality exist to withstand excessive floor heave and/or pillar punching; and

4. That existing mining depth and/or unique seam conditions do not prevent pillar yielding. An example of unique conditions exists at one Western U.S. mine where a combination of an extremely strong immediate roof and floor rock, high horizontal stresses, and a strong, nearly intact coal seam have resulted in severe face and pillar bumps (*22*). Field measurements indicated that the pillars did not yield, and that very narrow, possibly less than 6 m (20 ft), pillars may be necessary.

The ALPS (Analysis of Longwall Pillar Stability) method was modified by incorporating a coal mine roof rating system (CMRR). The CMRR provides an estimate of the quality of the bolted thickness of the immediate roof (*15-16*). The ALPS-CMRR method is specifically applicable to the design of full-support entry systems. A design equation is incorporated that calculates a CMRR-dependent stability factor for entry systems capable of supporting loads induced by second panel mining.

Figure 1 illustrates a conceptual relationship between gate road performance and pillar width (*5*). Of particular importance are the region delineating stable yielding pillar systems, and the avoidance of unstable, "critical" pillar widths, defined as widths too large to yield, yet too small to fully support overburden plus longwall-induced loads. DeMarco's (*5*) conceptual depiction of yield pillar feasibility infers a relationship between entry system performance and pillar width. Mark's CMRR-ALPS method quantifies a relationship between entry system stability and roof quality (*15-16*). The proposed yielding pillar sizing method assumes that yielding pillar entry system performance is also related to roof quality. Functions were derived that determine pillar sizes occupying the region of successful yield pillar systems, conceptually depicted in figure 1.

The analysis assumed that the following factors influenced entry system performance:

1. Roof quality, CMRR-based;
2. Pillar width-height ratio;
3. Depth;
4. Extraction ratio; and
5. Pillar strength.

As yielding systems undergo more deformation than abutment pillar systems, roof quality is of increased importance. Immediate roof classification provides a means for not only quantifying roof quality but for also determining whether yielding pillar systems may be viable. Roof quality was determined using the USBM-developed CMRR system (*17-18*). Molinda and Mark (*17*) provide details on data collection and step-by-step instructions; Riefenberg and Wuest (*18*) provide a PC spreadsheet for calculating CMRR. This method uses simple measurements and observations to estimate roof quality by assigning a numerical rating to the bolted thickness of the immediate roof. As with any classification system, the method is somewhat subjective, and the rating depends, in part, on experience and individual judgment.

The CMRR is based on the premise that the structural integrity of a mine roof is determined primarily by discontinuities. The following numerical rating is determined by summing the following weighted factors (*17*):

1. Discontinuity shear strength;
2. Discontinuity intensity;
3. Strength and weatherability of the rock;
4. Presence of a strong bed within the bolted interval;
5. Number of beds within the bolted interval;
6. Rock quality overlying the bolted interval; and
7. Quantity of water inflow.

Many pillar design techniques include shape effects, specifically the width-height ratio, and in some cases, pillar length (*12,19-21*). The width-height ratio significantly affects pillar strength. Although the width-height ratio does not influence the extent of rib yielding, the pillar width-height ratio should be such that complete yielding occurs. Experience indicates that many in-mine yield pillars have width-height ratios of 4 or less. Pillar length, or in some cases the ratio of pillar length-to-width, affects pillar strength (*20*). Pillar length was used to determine the development-induced extraction ratio. Extraction ratio is necessary for calculating the average, tributary pillar pressure, and provides a measure of the ground that can be safely "opened up" as a function of immediate roof quality. Pillar dimensions also contribute to the post-peak strength of the yielded pillar.

Several analytical methods are available that include the strength of a pillar comprised of yielded, or failed, coal (*6-8,11-12*). Although the details among the methods may differ, they agree that the strength of the failed coal and the extent of the yield zone result from frictional resistance and confining pressure that increase with distance into the rib. This analysis did not use yielded pillar strength, but instead quantified pillar behavior by comparing the average pillar pressure, calculated from assumed tributary loading, to the pillar strength based on Bieniawski's pillar design equation (*19*). This result, hereafter termed the *pillar development factor*, is not the "stability" factor of a yielded pillar, but is assumed to provide an index of the load, or pressure, required to **induce** pillar yielding. The pillar development factor is based on the assumptions that development loading could be approximated using tributary loading, and that the in situ coal seam strength is a constant 6.2 MPa (900 psi). Mark (*15*), from finite-element modeling and references to in situ studies, indicates that tributary loading satisfactorily approximates development loads on typical longwall pillars. Admittedly, this assumption requires further study.

Factors not incorporated into the analysis were horizontal stresses, floor conditions, and possibly most important, seam-specific postfailure behavior (*21*). Although documented for some samples, floor conditions were not included due to lack of a rating system and insufficient data; horizontal stress effects were also excluded due to incomplete data.

DATABASE DESCRIPTION AND STATISTICAL ANALYSIS

This study utilized a database constructed from a publication on yield and critical pillars (*5*), a summary of ground control studies at four, deep Western U.S. coal mines (*22*), a recently published historical summary of the Sunnyside mines (*1-2*), and from ongoing studies. The database, table 1, consists of 60 data sets from 12 Western U.S. mines, and includes input from 53 two-entry systems and 7 three-entry systems. The three-entry systems include both yield-yield and yield-abutment pillar configurations. The database includes immediate roof quality using the CMRR method; mine and/or panel-specific pillar width-height and extraction ratios; pillar development factors based on tributary area, overburden pressure, and the Bieniawski pillar strength formula; and entry system performance evaluations summarized in the above references. The database was augmented using estimated CMRR values for the roof descriptions provided in Koehler (*1-2*). In-mine Sunnyside measurements determined a CMRR of 75 to 80 for roof conditions described as very good, and a CMRR of 50 for roof conditions described as very poor (*5*). These ratings compare favorably with the general descriptions provided by Molinda (*17*) where roofs of CMRR exceeding 65 are classified as strong, and for those of CMRR less than 45 as weak. Using the above measured values as upper and lower limits, estimated CMMR values were assigned as follows:

Very good - 75;
Good - 65;
Fair - 60;
Poor - 55; and
Very Poor - 50.

DeMarco (*5*) includes an assessment of entry system performance that was followed for this analysis. Documented occurrences of either strata failures or coal bumps are deemed unsatisfactory (performance level 0); absence of these conditions is termed satisfactory (performance level 1). Although strata failures may result from factors not dependent upon pillar yielding, weak strata conditions may preclude the use of yielding pillar systems. Examination of table 1 indicates that unsatisfactory performance occurred when the CMRR value was less than 50.

The analysis assumed that documented entry system performance was related to the immediate roof quality and pillar behavior, and that pillar behavior could be quantified in terms of overburden pressure and entry system geometry. For each data set, pillar width-height ratios, development-induced extraction ratios, and the pillar development factors were calculated. Discriminant analysis was used to generate expressions for each of the above parameters as functions of the CMRR, and to separate the case histories into either satisfactory or unsatisfactory populations, performance levels 1 and 0, respectively. The discriminant analysis was performed for the 51 data sets having CMRR values exceeding 50. Data from mines 11 and 12 were obtained subsequent to deriving the discriminant equations; these data, however, are included in the table 2 comparison between in situ and generated, acceptable pillar sizes.

Figure 2 summarizes the pillar width-height ratio analysis. No satisfactorily performing entry systems were documented for CMRR values less than 50; unsatisfactory performance was attributed to roof and/or floor failures. A CMRR value of 50 was tentatively assigned as the *lower limit* of yield pillar system applicability. For CMRR values exceeding 50, unsuccessful performance resulted from coal bumps; the exception, sample 7, resulted from excessive floor heave.

Discriminant analysis was applied to data sets of CMRR exceeding 50; the relationship between the width-height ratio and CMRR is

$$\frac{W}{H} = 13.337 - 0.087\ \mathrm{CMRR}\,, \tag{1}$$

where W/H is the recommended **maximum** width-height ratio as a function of roof quality.

The width-height ratio versus CMRR statistical analysis indicated a 0.74 canonical correlation. The mean width-height ratios and standard deviations for the satisfactory and unsatisfactory performances were 4.6±0.9 and 9.3±3.6, respectively; the mean width-height ratio was 5.8.

As the database consisted primarily of two-entry systems that are generally applicable under bump-prone conditions, a "conservative" approach based on avoiding coal bumps was followed. It was assumed that pillars should yield upon development, and no later than approach of the first panel. Any later yielding significantly increases the likelihood of coal bumps and strata failures. For, multi-entry systems, generally used under shallower and/or nonbump-prone conditions, development-induced pillar yielding may not be necessary. Depending upon the post-peak strength and postfailure deformational behavior of the coal bed and adjacent strata, it may be possible to size pillars that yield at other mining stages (*21*). Field studies in multientry systems have observed pillar yielding after passage of the first panel without the occurrence of significant ground control problems (*14,22-23*).

The best practical means to enhance pillar yielding is through the proper selection of the width-height ratio. Equation 1 indicates that successful yield pillar width-height ratios decrease as roof quality increases. The equation establishes maximum, roof quality-dependent width-height ratios; the ratios range from approximately 4.4 to 7 at CMRR values of 50 to 80, respectively. Although a width-height ratio approaching 7 seems high, the database includes successful case histories with width-height ratios of 6, samples 15-17. As these samples are near the lower range of depths and seam heights, 300 m (1,000 ft) and 1.5 m (3 ft), respectively, and show development factors exceeding 1, it is highly probable that yielding occurred subsequent to development and with approach of the panel.

The observed relationship between roof quality and width-height ratio may be supported by both analytical and numerical modeling studies. Although yield zone development and subsequent pillar yielding is dependent upon a number of factors not included in this analysis, other studies indicate that yield zone extent is greater when the coal seam is located between weaker strata (*9-11*).

Figure 3, extraction ratio versus CMRR, shows that successful entry systems occupy a region defined by

$$ER = 0.355 + 0.002\ CMRR\,, \tag{2}$$

where ER equals the extraction ratio resulting from *pillar development.*

The extraction ratio discriminant analysis resulted in a 0.763 correlation coefficient. The mean values and standard deviations for the successful and unsuccessful performance levels were 0.50±0.07 and 0.39±0.03, respectively. The sample mean extraction ratio was 0.47. Equation 2 establishes the **minimum**, roof quality-dependent extraction ratio; these ratios range from 0.45 to 0.50 at CMRR values of 50 and 80, respectively. Satisfactory performances were documented for extraction ratios of up to 0.55. Increased extraction ratio with increasing roof quality suggest that a larger area of ground can be excavated. Pillar length, one component of extraction ratio, contributes to both the peak and post-peak, pillar support capacity. Although most pillar strength determinations usually include the width-height ratio, several design methods also include the ratio of pillar length-to-pillar width (*20*). The ALPS method utilizes pillar length to calculate pillar capacity (*15-16*). Pillar design methods based on the confined core approach and/or progressive pillar failure also utilize pillar dimensions to calculate pillar capacity. Dependent upon yield zone extent, total pillar capacity is determined by summing the support capacity provided by the yielded and intact portions of the pillar (*6-7,11-12*).

The relationship between the development factor and CMRR is shown in figure 4; the derived discriminant being

$$DF = 2.06 - 0.02\ CMRR \tag{3}$$

where DF equals the **maximum** development factor.

The statistical analysis indicated a canonical correlation of 0.63; this correlation was the lowest of the three derived functions. Possible reasons include the validity of assumed tributary loading and use of a constant in situ coal seam strength, 6.2 MPa (900 psi). The means and standard deviations were calculated to be 1.12±0.5 and 0.65±0.24 for the unsatisfactory and satisfactory performance levels, respectively. The development factor (DF) is the ratio of the pillar strength, based on the Bieniawski pillar formula, to the tributary load resulting from development, or

$$DF = \frac{S_p}{\sigma_{tr}}, \tag{4}$$

$$S_p = 900\ (0.64 + 0.36\ \frac{w}{h}), \tag{5}$$

$$\sigma_{tr} = (\ \frac{A_m}{A_t}\ ), \tag{6}$$

where DF = development factor,
S_p = pillar strength,
σ_{tr} = tributary pressure,
w/h = width-height ratio,
A_t = total area, pillar and openings, and
A_m = pillar area.

As presented earlier, the development factor was assumed to provide a measure (index) of whether development loading could induce pillar yielding. Examination of table 1 indicates that, except for the three cases previously discussed under pillar width-height ratio, satisfactory performance resulted when the development factor was less than 1. Unsatisfactory performance, in most cases, occurred when the pillar development factor exceeded 1. Many of these unsuccessful cases are comprised of pillars having width-height ratios exceeding 7, the **maximum** allowable value from expression 1 at a CMRR value of 50. To test whether these large width-height ratio pillars corresponded to the "critical" pillar widths defined by DeMarco (*5*), tailgate loading stability factors were calculated and compared to the ALPS stability factor (*16*). Figure 5 clearly indicates that the stability factors of the unsuccessful, large width-height ratio pillars were insufficient to meet the imposed loads. As these pillars were too wide to yield yet insufficiently wide to support the applied loads, it is concluded that these pillars are "critical" pillars. Using the ALPS safety factor, figure 5, and the development factor-CMRR relationship, figure 4, avoiding "critical" widths requires that the pillar be either wide enough to satisfy the minimum ALPS stability factor, shown in figure 5, or narrow enough to meet the development factor derived in this study. Intermediate pillar widths are "critical."

PILLAR SIZING METHOD

The statistical analysis indicated that yielding pillar performance could be expressed in terms of the width-height ratio, extraction ratio, and a pillar development factor as functions of the roof quality, CMRR. Successfully performing pillar systems, for CMRR greater than 50, are assumed to consist of those configurations that meet all of the following criteria:

1. Pillar width-height ratio must not exceed the **maximum** value as determined from the width-height-CMRR relationship;
2. The pillar development factor must not exceed the **maximum** value allowed by the development factor-CMRR expression;
3. The development-induced extraction ratio must be no less than the **minimum** allowable value from the extraction ratio-CMRR relation;
4. A CMRR value of less than 50 is tentatively assigned as the *lower limit of yielding pillar applicability.*

A program, Pillar Sizer, described more fully in the appendix, generates a graphical display of yield pillar sizes meeting the above three criteria. The program is available from the National Technical Information Service, 1-800-553-NTIS. Pillar Sizer runs in a Windows environment, displays inputs and results both numerically and graphically, and includes on-screen instructions and a HELP menu. The user inputs the depth, seam height, entry width, and CMRR; both metric and English units are available. Pillar widths are bounded by a **maximum** value, defined by the CMRR-width-height ratio relationship, and a **minimum** of 6.1 m (20 ft). This minimum value represents the minimum, operationally acceptable pillar width (5). Maximum pillar length was arbitrarily set at 61 m (200 ft); the minimum pillar length, 24 m (80 ft) approximates database values for the lower limit of pillar lengths. Pillar length selection is as much an operational decision as a design problem; any pillar length-width combination meeting the above three criteria is assumed acceptable. The range of depths and seam heights, based on the database, are 240 m to 900 m (800 ft to 3,000 ft) and 1.5 m to 3 m (5 ft to 10 ft), respectively. The in situ seam strength is assumed to be 6.2 MPa (900 psi).

Table 2 shows a comparison between the in-mine yield pillar sizes and PSIZER-generated pillar sizes. Where possible, the PSIZER-generated pillar widths are for the same pillar lengths as their in-mine counterparts. The range of acceptable pillar sizes exceed those shown in the table. In most cases, the calculated pillar sizes closely approximated in-mine pillars. Excluding samples 7, 37, and 38, unsatisfactory performance cases (performance level 0) occurred when the pillar width-height ratios were too large. Sample 7 was deemed unsuccessful due to excessive floor heave; samples 37 and 38 are near the lower range of depths. For some samples, the generated pillar widths were less than those of successfully performing in situ yield pillars. One plausible explanation is that pillar yielding occurred not with development, but with approach and/or passage of the longwall face. Limited field measurements show that some pillars yielded after passage of the first face (*14*,*22*). Table 2 includes additional data from mines 11 and 12; both mines use three-entry systems with one abutment and one yielding pillar. For both mines, the PSIZER-generated yield pillar widths closely bounded the in-mine pillar sizes. Measurements at both mines indicated that pillar yielding occurred when the face was approximately 60 m (200 ft) outby.

DISCUSSION AND RECOMMENDATIONS FOR FUTURE STUDY

The proposed empirical method generates pillar sizes that generally agree with in-mine observations. Refinement and validation of this technique require additional field measurements, consisting of a wider range of depths, seam heights, and strata conditions. Future studies should ideally include both floor and seam characterization as well as a wider range of entry widths and documentation of roof support performance. This approach utilized a performance rating that was based solely on the occurrence, or lack, of ground failures. The comparison between generated versus in-mine pillar sizes, table 2, indicates that overly wide pillars may provide satisfactory performance. The requirement that pillars yield on development is probably too stringent, especially for three-entry systems and/or under moderate roof conditions, CMRR values less than 65. The requirement that pillars yield with development was based on historical experience with two-entry systems under bump-prone conditions, i.e. depth and a strong roof.

The correlation between CMRR and the development factor, approximately 0.63, was not as strong as desirable. The development factor was included to account for depth, and to determine whether yielding could be induced. The development factor was based on the assumptions that pillar loading could be approximated using tributary area, and that pillar strength could be accurately based on an in situ seam strength of 6.2 MPa (900 psi). The validity of both these assumptions requires further study. As the development factor also includes both the extraction ratio and depth, its use may be redundant. Possible alternatives include the ratio of vertical stress to in situ seam strength or the ratio of vertical stress to pillar strength.

The proposed pillar sizing approach calculated pillar strengths using an assumed in situ coal seam strength of 6.2 MPa (900 psi). Western U.S. coal seams, however, often reveal a wide variation in structural characteristics, ranging from highly cleated to almost intact. Kalamaris (*24-25*) has recently proposed a method to determine in situ seam strength based on a coal seam classification method. This technique assigns a numerical rating to coal seams based on the sample (cleat body) strength, discontinuity density and condition, seam heterogeneity, and face cleat-to-opening orientation. Other adjustments include, among others, the immediate roof strata type, lubrication due to water and mineral content, fault location, and blasting effects. A more recently published modification uses the dimensions of fallen rib coal to approximate discontinuity spacing (*26*). Charts are provided for converting in-mine measurements to numerical ratings, and the opening-to-face cleat adjustment is simplified.

Maleki (*21,27*) from in situ studies, proposed two pillar failure mechanisms that are based on coal seam structure. Elastic-plastic behavior occurs in seams with in-seam or near seam weakness planes. Beyond peak stress, deformation occurs at constant stress and is followed by strain softening. Elastic-residual behavior occurs in highly cleated coal seams; beyond peak strength, the average pillar stress drops to a residual strength. From in situ tests and observations in eight U.S. coal mines, two best-fit equations are presented that relate average pillar strength to the pillar width height ratio. The high strength (confinement controlled) curve is typical for mines with a large degree of pillar confinement. The low strength (structural controlled) curve is typical for seams that include persistent cleats and in-seam contact planes. The high and low strength curves are (*21*)

$$SCS = 4700\ (1 - EXP(-0.339\ \frac{w}{h})) \tag{7}$$

$$CCS = 3836\ (1 - EXP(-0.260 \frac{w}{h})) \tag{8}$$

where

SCS = structurally controlled average pillar strength, psi,
CCS = confinement controlled average pillar strength, psi,
w/h = pillar width-height ratio, and
EXP = exponential function.

Another method to determine coal seam strength is through testing; a recently developed method uses a hydraulically actuated penetrometer in horizontal boreholes (*28*). Regardless of the method, future studies should include more accurate determination of in situ coal seam strength.

SUMMARY

The proposed approach generates the dimensions of longwall entry yielding pillars satisfying criteria derived from a statistical analysis of Western U.S. case studies. The three criteria: width-height ratio, extraction ratio, and a pillar development factor are expressed as functions of the immediate roof quality, determined using the USBM-developed CMRR method. A program Pillar Sizer generates from user-supplied inputs a range of pillar widths and lengths meeting the criteria. The technique although specifically applicable to two-entry systems, generally used in deep bump-prone conditions, may also be valid for sizing multientry, yield pillar systems. For two-entry systems, pillar yielding upon development was assumed to be desirable for minimizing the risks of coal bumps. For three-entry systems, generally used under less deep and less bump-prone conditions, development with first panel mining may be acceptable. Additional field investigations are highly recommended not only for corroborating the proposed approach but also for expanding its potential application. Future studies should include coal seam characterization, floor strata characterization, and, if possible, in situ stress measurements.

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Table 1.—Entry system database.

Sample	Mine	Coal mine roof rating	Performance[1]	Extraction ratio	Development factor	W/H ratio	Number of entries	Entry width, m	In-mine pillar width by length, m	Depth, m	Panel width, m	Seam height, m
1	1	75	1	0.51	0.43	3.8	2	6.1	9 by 26	550	152	2.4
2	2	80	1	0.51	0.42	3.8	2	6.1	9 by 26	550	152	2.4
3	3	60	1	0.48	0.55	3.8	2	5.5	9 by 26	460	155	2.4
4	3	60	1	0.44	0.61	3.53	2	5.5	11 by 24	460	155	2.6
5	3	60	1	0.44	0.79	4.1	2	5.5	11 by 31	365	155	2.6
6	3	60	0	0.38	1.02	6.9	3	5.5	17 by 24	460	155	2.4
7	4	75	0	0.52	0.78	4.3	2	6.1	9 by 24	350	158	2.1
8	4	75	0	0.4	0.97	7.1	2	6.1	15 by 32	490	158	2.1
9	4	70	0	0.4	1.54	7.1	2	6.1	15 by 32	305	158	2.1
10 . . .	4	75	0	0.27	2	17.1	2	6.1	37 by 37	610	158	2.1
11 . . .	4	75	0	0.27	2.22	15	2	6.1	32 by 43	490	158	2.1
12 . . .	5	75	0	0.4	0.99	10	2	6.1	24 by 18	490	131	2.4
13 . . .	5	33	0	0.51	0.53	4.3	2	6.1	9 by 26	490	131	2.1
14 . . .	6	80	1	0.49	0.31	4.3	2	6.1	9 by 34	850	182	3.1
15 . . .	6	63	1	0.49	1.14	6	2	6.1	9 by 34	305	152	1.5
16 . . .	6	63	1	0.49	1.14	6	2	6.1	9 by 34	305	152	1.5
17 . . .	6	63	1	0.49	1.14	6	2	6.1	9 by 34	305	152	1.5
18 . . .	6	68	1	0.51	0.96	5	2	6.1	9 by 27	305	152	1.8
9	6	68	1	0.54	0.52	4.2	2	6.1	8 by 29	305	152	1.8
20 . . .	6	68	1	0.48	0.75	5.8	2	6.1	11 by 26	460	152	1.8
21 . . .	6	68	1	0.48	0.56	5.8	2	6.1	11 by 26	610	152	1.8
22 . . .	6	65	1	0.54	0.83	4.5	2	6.1	8 by 29	305	140	1.7
23 . . .	6	65	1	0.54	0.83	4.5	2	6.1	8 by 29	305	140	1.7

See explanatory note at end of table.

Table 1.—Entry system database—Continued

Sample	Mine	Coal mine roof rating	Performance[1]	Extraction ratio	Development factor	W/H ratio	Number of entries	Entry width, m	In-mine pillar width by length, m	Depth, m	Panel width, m	Seam height, m
24 . . .	6	58	1	0.53	0.4	4.2	2	6.1	8 by 34	610	140	1.8
25 . . .	6	58	1	0.52	0.41	4.2	2	6.1	8 by 40	610	140	1.8
26 . . .	6	58	1	0.55	0.52	4.2	2	6.1	8 by 27	460	140	1.8
27 . . .	6	58	1	0.55	0.39	4.2	2	6.1	8 by 27	610	140	1.8
28 . . .	6	58	1	0.56	0.51	4.2	2	6.1	8 by 24	460	140	1.8
29 . . .	6	58	1	0.48	0.68	5	2	6.1	9 by 40	460	140	1.8
30 . . .	6	60	1	0.5	0.55	6	2	6.1	9 by 29	610	226	1.5
31 . . .	6	60	1	0.5	0.55	6	2	6.1	9 by 29	610	226	1.5
32 . . .	6	60	1	0.5	0.74	6	2	6.1	9 by 29	460	226	1.5
33 . . .	6	60	1	0.51	0.48	5	2	6.1	9 by 27	610	91	1.8
34 . . .	6	60	1	0.51	0.48	5	2	6.1	9 by 27	610	91	1.8
35 . . .	6	65	1	0.5	0.49	5	2	6.1	9 by 30	610	91	1.8
36 . . .	6	65	1	0.45	0.53	5	2	6.1	9 by 61	610	91	1.8
37 . . .	6	58	0	0.45	1.06	5	2	6.1	12 by 27	305	182	2.4
38 . . .	6	58	0	0.45	0.71	5	2	6.1	12 by 27	380	182	2.4
39 . . .	6	58	1	0.49	0.85	3.8	2	6.1	9 by 34	610	182	2.4
40 . . .	6	55	1	0.49	0.4	3.8	2	6.1	9 by 34	610	182	2.4
41 . . .	6	55	1	0.49	0.32	3.8	2	6.1	9 by 34	760	182	2.4
42 . . .	6	55	1	0.49	0.32	3.8	2	6.1	9 by 34	760	182	2.4
43 . . .	6	80	0	0.38	0.61	7.9	2	6.1	17 by 34	860	182	2.1
44 . . .	6	68	0	0.44	1.5	7.5	2	6.1	14 by 26	305	152	1.8
45 . . .	6	60	0	0.44	0.76	7.5	2	6.1	14 by 27	610	91	1.8
46 . . .	6	60	0	0.39	0.94	10	2	6.1	18 by 27	610	91	1.8

See explanatory note at end of table.

Table 1.—Entry system database—Continued

Sample	Mine	Coal mine roof rating	Performance[1]	Extraction ratio	Development factor	W/H ratio	Number of entries	Entry width, m	In-mine pillar width by length, m	Depth, m	Panel width, m	Seam height, m
47 . . .	6	60	0	0.35	1.33	12.5	2	6.1	23 by 27	610	91	1.8
48 . . .	6	60	0	0.44	0.76	7.5	2	6.1	14 by 27	610	91	1.8
49 . . .	6	50	0	0.5	0.37	4.3	2	6.1	9 by 34	730	182	2.1
50 . . .	7	55	1	0.5	0.86	3	3	6.1	9 by 32	240	182	3
51 . . .	7	65	1	0.5	0.8	3.5	3	6.1	9 by 30	290	182	2.6
52 . . .	7	77	1	0.5	0.8	3.5	3	6.1	9 by 30	290	182	2.6
53 . . .	7	65	1	0.5	0.8	3	3	6.1	9 by 30	290	182	2.7
54 . . .	8	38	0	0.36	1.81	5.9	2	5.5	13 by 59	240	152	2.4
55 . . .	8	50	0	0.49	1.08	4	2	5.5	10 by 30	245	152	2.4
56 . . .	9	43	0	0.28	2.5	10	2	5.5	30 by 30	335	182	3
57 . . .	9	35	0	0.36	2.22	10	2	5.5	9 by 17	335	182	3
58 . . .	10	33	0	0.48	1.7	3.8	2	5.5	9 by 27	150	174	2.4
59 . . .	11	65	1	0.41	0.84	3.7	3	5.5	7 by 46	335	182	2.9
60 . . .	12	63	1	0.48	0.71	3.9	3	6.1	9 by 26	305	182	2.7

[1]0 = unsatisfactory; 1 = satisfactory.

Table 2.—Comparison of calculated versus in-mine pillar sizes.

Sample	Mine	Coal mine roof rating	Performance[1]	Extraction ratio	Development factor	W/H ratio	In-mine pillar width by length, m	Calculated pillar width by length, m
1	1	75	1	0.51	0.43	3.8	9 by 26	8-9.1 by 26
2	2	80	1	0.51	0.42	3.8	9 by 26	8-8.5 by 26
3	3	60	1	0.48	0.55	3.8	9 by 26	6.7-9 by 26
4	3	60	1	0.44	0.61	3.53	11 by 24	7.3-9.8 by 24
5	3	60	1	0.44	0.79	4.1	11 by 31	6.7-8.5 by 31
6	3	60	0	0.38	1.02	6.9	17 by 24	7.3-9.8 by 24
7	4	75	0	0.52	0.78	4.3	9 by 24	6 by 55-61
8	4	75	0	0.4	0.97	7.1	15 by 32	7.8-8.5 by 32
9	4	70	0	0.4	1.54	7.1	15 by 32	7 by 38
10 ...	4	75	0	0.27	2	17.1	37 by 37	7.3-7.9 by 37
11 ...	4	75	0	0.27	2.22	15	32 by 43	6.7-7.3 by 43
12 ...	5	75	0	0.4	0.99	10	24 by 18	8 by 24
14 ...	6	80	1	0.49	0.31	4.3	9 by 34	7.3-7.9 by 34
15 ...	6	63	1	0.49	1.14	6	9 by 34	6 by 56
16 ...	6	63	1	0.49	1.14	6	9 by 34	6 by 56
17 ...	6	63	1	0.49	1.14	6	9 by 34	6 by 56
18 ...	6	68	1	0.51	0.96	5	9 by 27	6 by 56
19 ...	6	68	1	0.54	0.52	4.2	8 by 29	6 by 56
20 ...	6	68	1	0.48	0.75	5.8	11 by 26	7.9-9.8 by 26
21 ...	6	68	1	0.48	0.56	5.8	11 by 26	7.9-9.5 by 26
22 ...	6	65	1	0.54	0.83	4.5	8 by 29	6.7 by 38
23 ...	6	65	1	0.54	0.83	4.5	8 by 29	6.7 by 38
24 ...	6	58	1	0.53	0.4	4.2	8 by 34	7.3-9.8 by 34
25 ...	6	58	1	0.52	0.41	4.2	8 by 40	6.7-9.1 by 40
26 ...	6	58	1	0.55	0.52	4.2	8 by 27	8-11 by 27
27 ...	6	58	1	0.55	0.39	4.2	8 by 27	8-11 by 27
28 ...	6	58	1	0.56	0.51	4.2	8 by 24	8-11 by 24
29 ...	6	58	1	0.48	0.68	5	9 by 40	6.7-9.3 by 40
30 ...	6	60	1	0.5	0.55	6	9 by 29	7.3-9.4 by 29
31 ...	6	60	1	0.5	0.55	6	9 by 29	7.3-9.4 by 29
32 ...	6	60	1	0.5	0.74	6	9 by 29	7.3-9.1 by 29
33 ...	6	60	1	0.51	0.48	5	9 by 27	7.9-11 by 27
34 ...	6	60	1	0.51	0.48	5	9 by 27	7.9-11 by 27
35 ...	6	65	1	0.5	0.49	5	9 by 30	7.3-9.8 by 30
36 ...	6	65	1	0.45	0.53	5	9 by 61	6.1-7.9 by 61
37 ...	6	58	0	0.45	1.06	5	12 by 27	7.9 by 27
38 ...	6	58	0	0.45	0.71	5	12 by 27	7.9-9.8 by 27
39 ...	6	58	1	0.49	0.85	3.8	9 by 34	7.3-9.8 by 34
40 ...	6	55	1	0.49	0.4	3.8	9 by 34	7.3-9.8 by 34
41 ...	6	55	1	0.49	0.32	3.8	9 by 34	7.3-10.4 by 34
42 ...	6	55	1	0.49	0.32	3.8	9 by 34	7.3-10.4 by 34

See explanatory note at end of table.

Table 2.—Comparison of calculated versus in-mine pillar sizes—Continued

Sample	Mine	Coal mine roof rating	Performance[1]	Extraction ratio	Development factor	W/H ratio	In-mine pillar width by length, m	Calculated pillar width by length, m
43 . . .	6	80	0	0.38	0.61	7.9	17 by 34	7.3-7.9 by 34
44 . . .	6	68	0	0.44	1.5	7.5	14 by 26	6 by 56-61
45 . . .	6	60	0	0.44	0.76	7.5	14 by 27	7.9-11 by 27
46 . . .	6	60	0	0.39	0.94	10	18 by 27	7.9-11 by 27
47 . . .	6	60	0	0.35	1.33	12.5	23 by 27	7.9-11 by 27
48 . . .	6	60	0	0.44	0.76	7.5	14 by 27	7.9-11 by 27
51 . . .	7	65	1	0.5	0.8	3.5	9 by 30	7.3-8.5 by 30
52 . . .	7	77	1	0.5	0.8	3.5	9 by 30	None
53 . . .	7	65	1	0.5	0.8	3	9 by 30	7.3-8.5 by 30
59 . . .	11	65	1	0.41	0.84	3.7	7 by 46	6.1-7.3 by 46
60 . . .	12	63	1	0.48	0.71	3.9	9 by 26	7.9-9.8 by 26

[1]0 = unsatisfactory; 1 = satisfactory.

APPENDIX A.-DESCRIPTION AND USE OF THE PILLAR SIZER PROGRAM

By Alan D. Rock[1]

Pillar Sizer is a Windows-based software program for estimating yield pillar dimensions.

Developed by the U.S. Bureau of Mines, Pillar Sizer generates a graphical display of yield pillar dimensions satisfying criteria derived from a statistical analysis of over 50 case studies from 12 Western U.S. longwall mines. The three criteria, pillar width-height ratio, extraction ratio, and a pillar development factor, are expressed as functions of roof quality using the Bureau-developed coal mine roof rating method (CMRR). These criteria define *limiting values* for successful yield pillar entry systems. The width-height ratio and development factor represent maximum allowable values; the extraction ratio is a minimum allowable value. Graphically displayed are all yield pillar sizes meeting the three criteria, figure A-1. The program allows use of either English or metric units, and includes a Help menu and Optimizing feature for selecting pillar dimensions.

INSTALLATION

1. Start Windows;
2. Insert disk in drive A or B;
3. From Program Manager, select File menu and choose Run;
4. Type **a or b:\setup** and press ENTER

A series of installation screens will appear. The user can select either the default directory or their own. The user can install the Pascal source code by clicking the source code box and then continue; otherwise simply click the continue button. In some cases, a Warning- Cannot copy file A:\DDEMO.DL_ or file A:\DDEML.DLL may appear. If occurring, press the ENTER key; Pillar Sizer installation should continue.

LIMITATIONS

Pillar Sizer is based on data from Western U.S. longwall mines. The underlying discriminant equations are valid **only** for inputs lying within limits comprising the present data base. Inputs not within the allowable limits display a red background and

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[1]Mathematician, Denver Research Center, U.S. Bureau of Mines, Denver, CO; developed the Windows-based version of the Pillar Sizer program including the optimizing feature for selecting yielding pillar sizes.

are accompanied by a message showing the input and allowable ranges. The present version (1.0), does **not** permit use of inputs exceeding the ranges shown below:

CMRR 50-80;
Depth 240-860 m (800-3000 ft);
Seam height 1.5-3 m (5-10 ft);
Opening width 4.9-6.1 m (16-20 ft);
Pillar length 24-61 m (80-200 ft);
Seam strength 6.2 MPa (900 psi); and
Panel width.

The CMRR limits were based on observations. No successful entry systems were documented for values less than 50. That a larger number of solutions exist at lower CMRR values than at high CMRR values is due, in part, to the minimum allowable pillar width of 6.1 m (20 ft). This value, based on two-entry systems, is the minimum pillar width that is operationally feasible.

Allowable depth and seam height ranges reflect data base minimum and maximum values. Seam heights were based on development mining, although the data base includes mines that extract seam heights exceeding 3.1 m (10 ft) on the retreat.

The allowable range of entry widths was expanded to include 4.9 m (16 ft) openings.

Pillar lengths were based on the data base limits, 24-61 m (80-200 ft.); one unsuccessful case used 18 m (60 ft) pillar lengths. Most western U.S. mines utilize pillar lengths within the suggested ranges. Pillar widths were allowed to vary between the minimum allowable width, 6.1 m (20 ft), and a maximum defined by either the width-height ratio versus CMRR relationship or 60 ft.

Pillar strength was calculated using the Bieniawski pillar strength formula which assumes an in situ seam strength of 6.2 MPa (900 psi). The pillar development factor versus CMRR is based on this assumed seam strength. Use of other values is not applicable. Future versions may allow user provided seam strengths.

Panel width has **no** effect on development-induced pillar loading. Panel width was included for future versions that will incorporate post-development yielding.

RUNNING PILLAR SIZER

Getting Started

1. Click on the Pillar Sizer icon;

2. Select units, metric or English, and input data in appropriate boxes. Invalid inputs will be flagged in red.
3. To view acceptable pillar sizes, click the mouse in any **valid** pillar size box (those with white backgrounds).

Help Menu

The Help menu includes a full description of the input and output screens. Clicking the mouse on any input box will show the appropriate allowable range. The Help menu output displays a grid of acceptable pillar sizes. Clicking the mouse in any of the white rectangles generates numerical outputs and a rectangle displaying the currently selected valid pillar size. Adjacent to the numerical output boxes are colored squares that correspond to the perimeter of the acceptable pillar size grid. Red grid points delineate the maximum and minimum pillar lengths and widths. Extraction ratio limits are denoted by light and dark blue.

Selecting Pillar Sizes

Selection of pillar sizes is activated by selecting Search and then Optimum from the menu. This feature assists selection of pillar sizes from the range of generated acceptable pillars. The user can select and weight, by importance, any one or combination of pillar length, pillar width, width-height ratio, extraction ratio, and/or development factor, figure A-2. The output frame is expanded to allow selection of the searching criteria. Valid pillar sizes are color-coded to correspond to the adjacent color scale. Those pillar sizes most closely matching the criteria correspond to the color at the top of the scale; those with the lowest match correspond to the color at the bottom of the scale. If none of the criteria are selected, the acceptable pillar size grid is shown in the color corresponding to the bottom of the scale. The criteria are selected and weighted by inserting desired search values and by selecting the appropriate importance button.

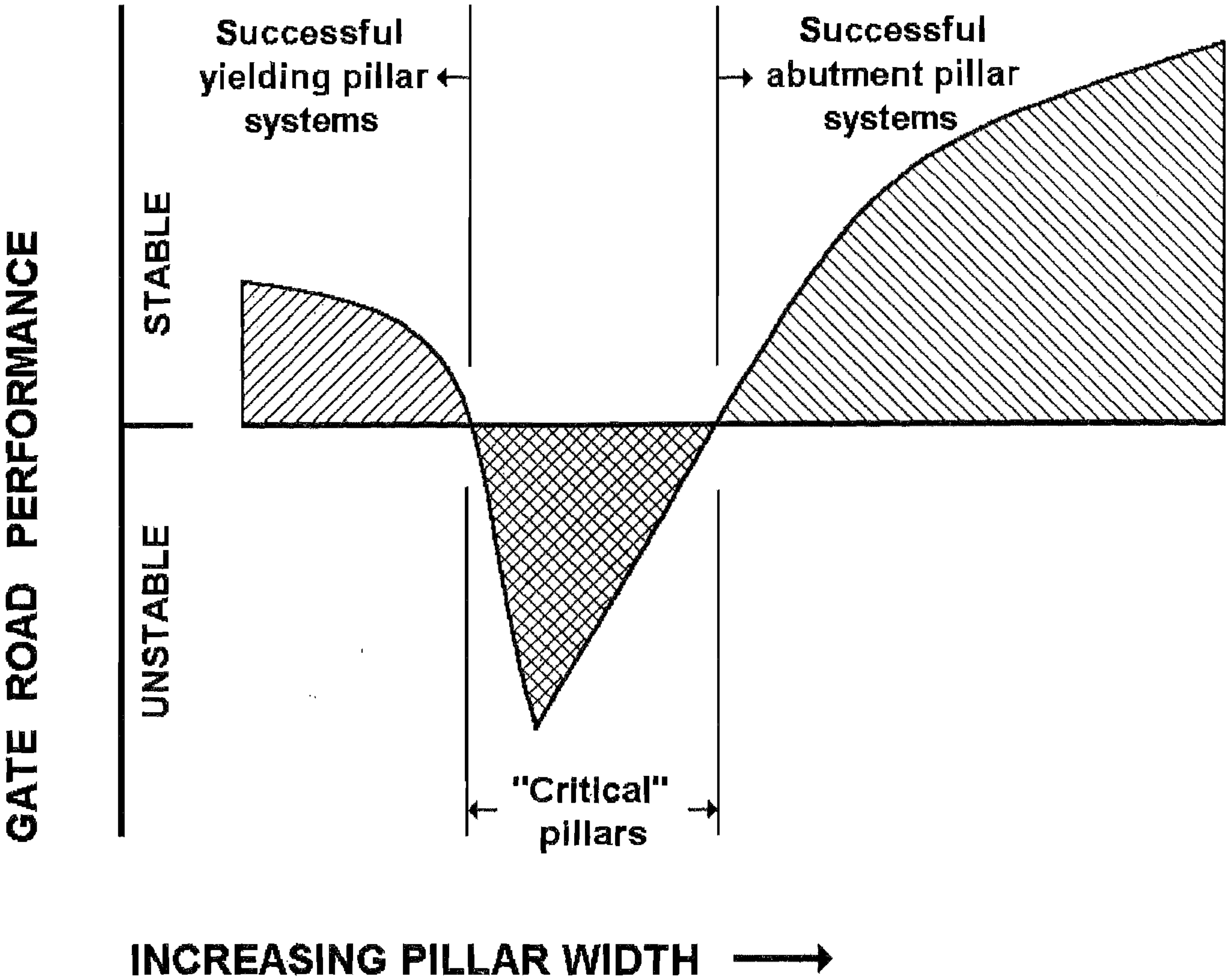

Figure 1. Conceptualization of the critical pillar relationship showing the transition from successful yield pillar systems, through unsuccessful designs, to successful abutment pillar systems (*5*).

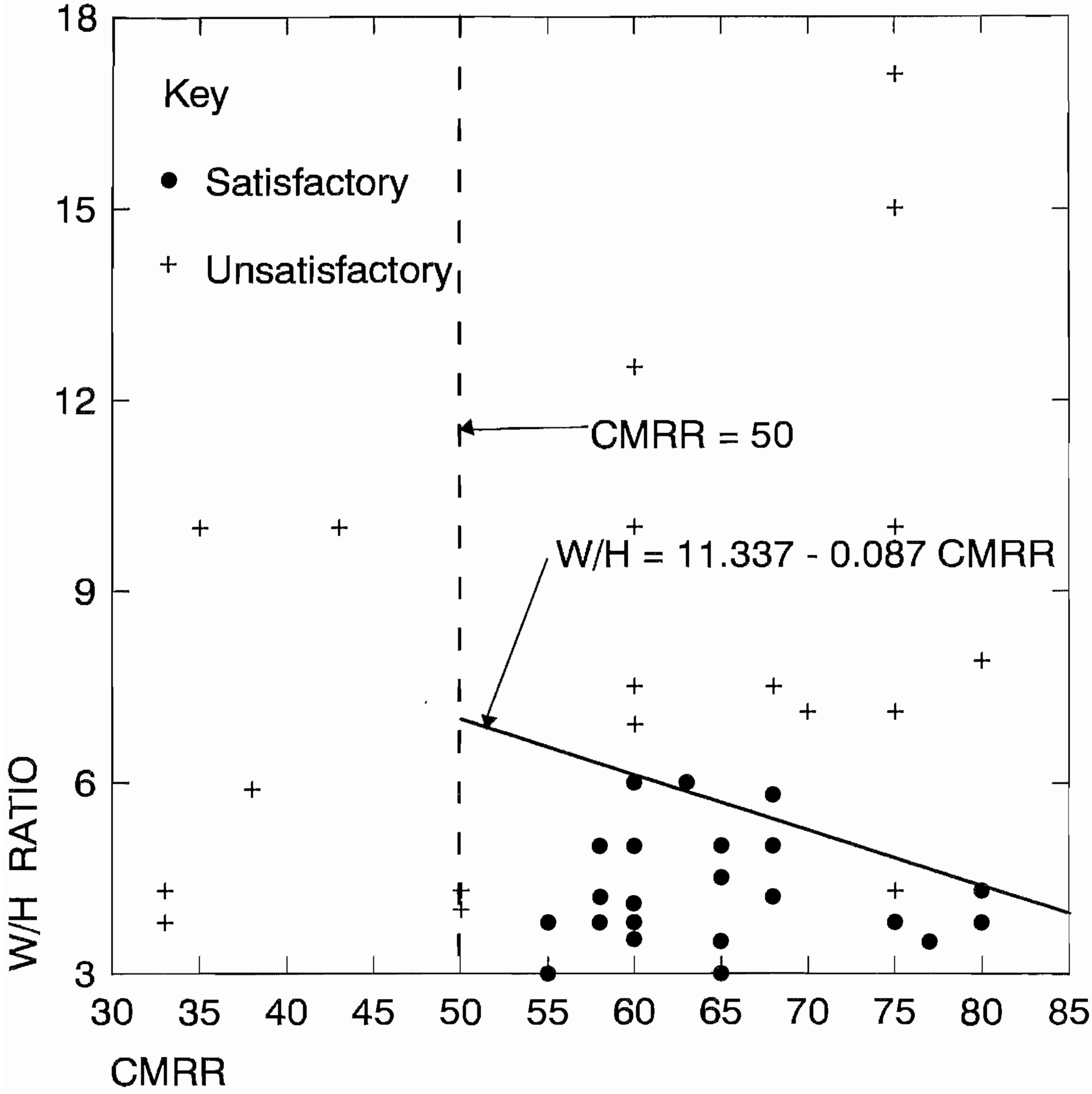

Figure 2. Scatter plot of case histories showing the discriminant equation derived from the analysis of the Coal Mine Roof Rating (CMRR) and in-mine pillar width-height ratios (W/H).

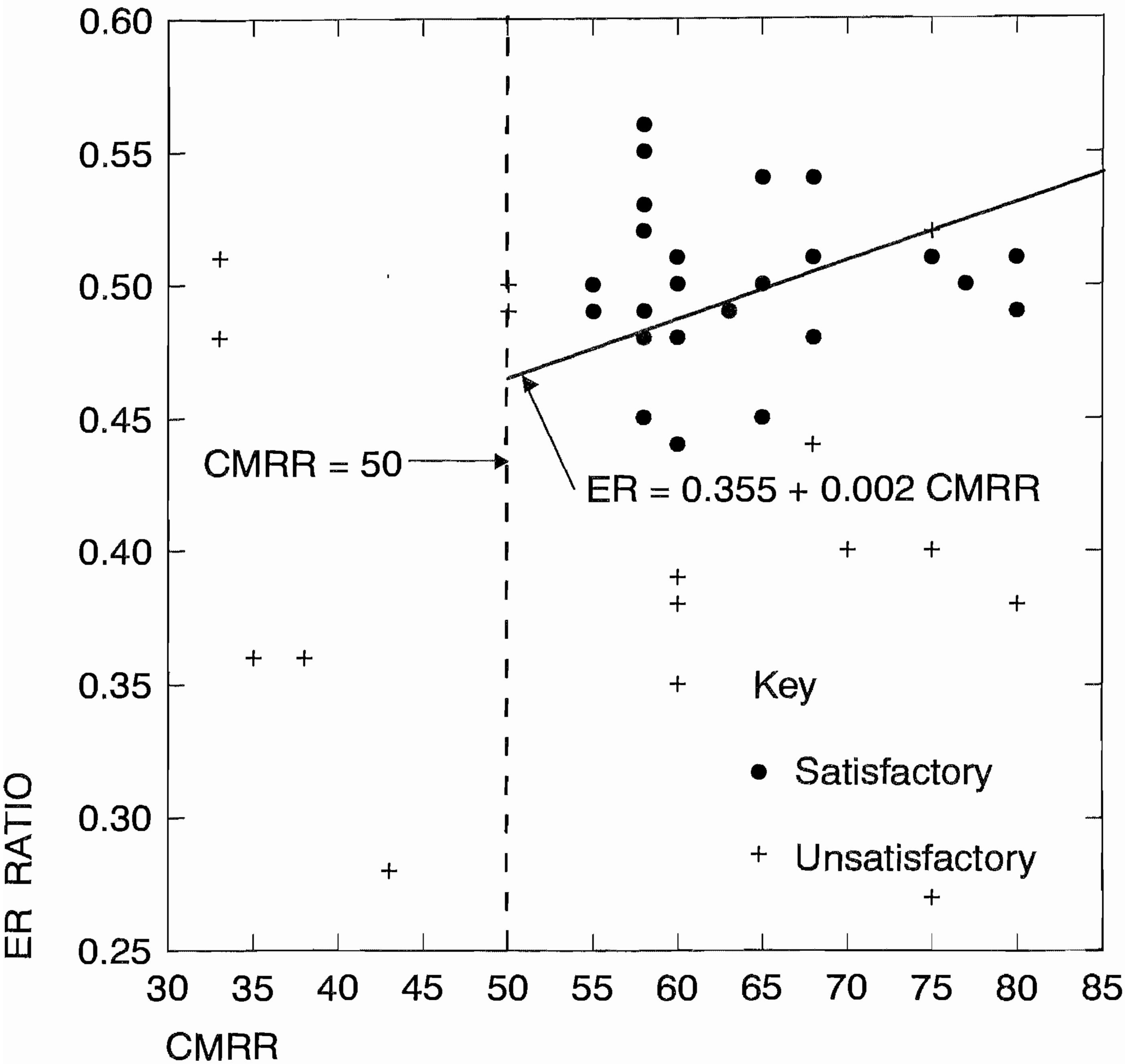

Figure 3. Scatter plot of case histories showing the discriminant equation derived from the analysis of CMRR and in-mine extraction ratios (ER).

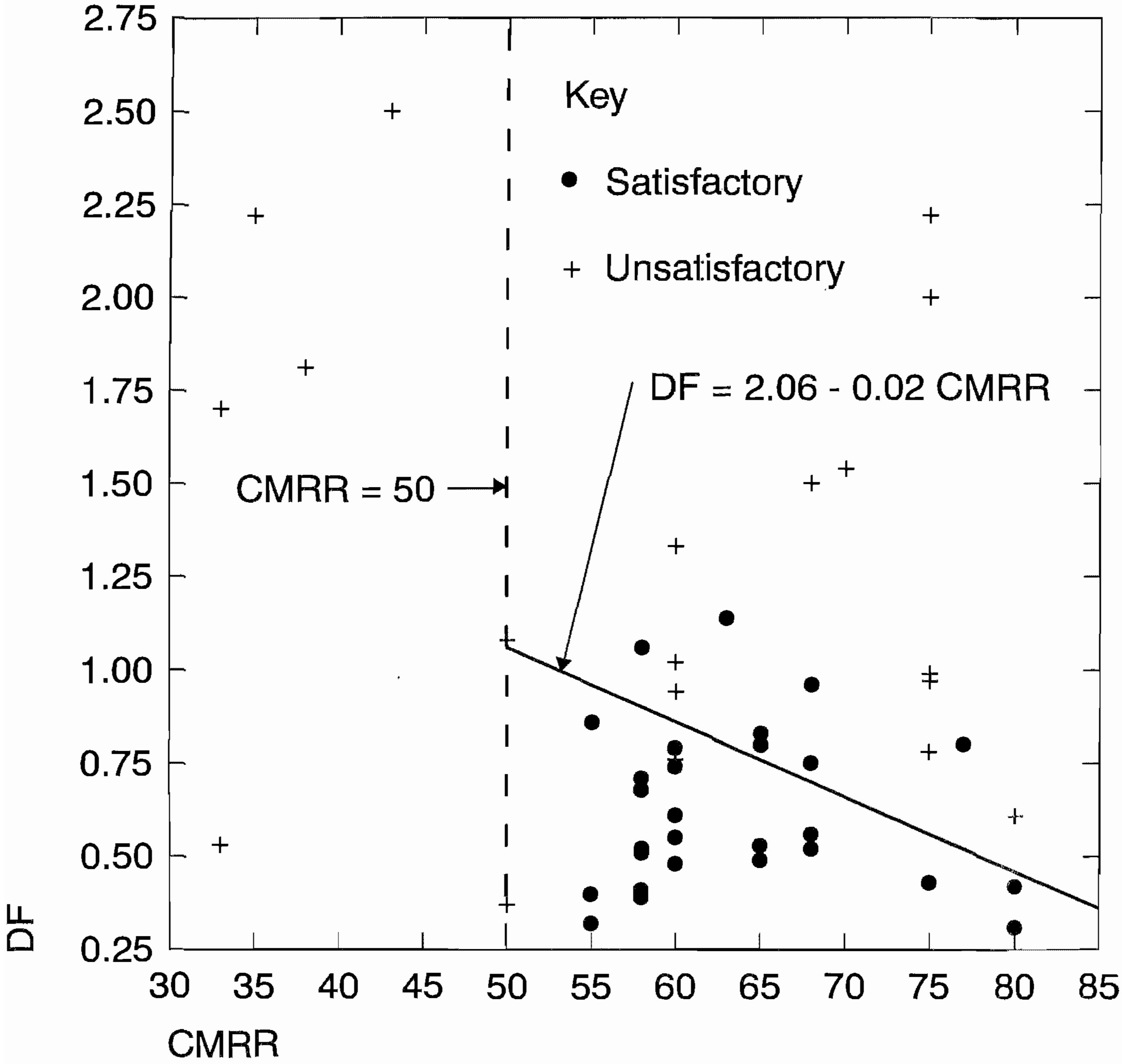

Figure 4. Scatter plot of case histories showing the discriminant equation derived from the analysis of CMRR and in-mine pillar development factor (DF).

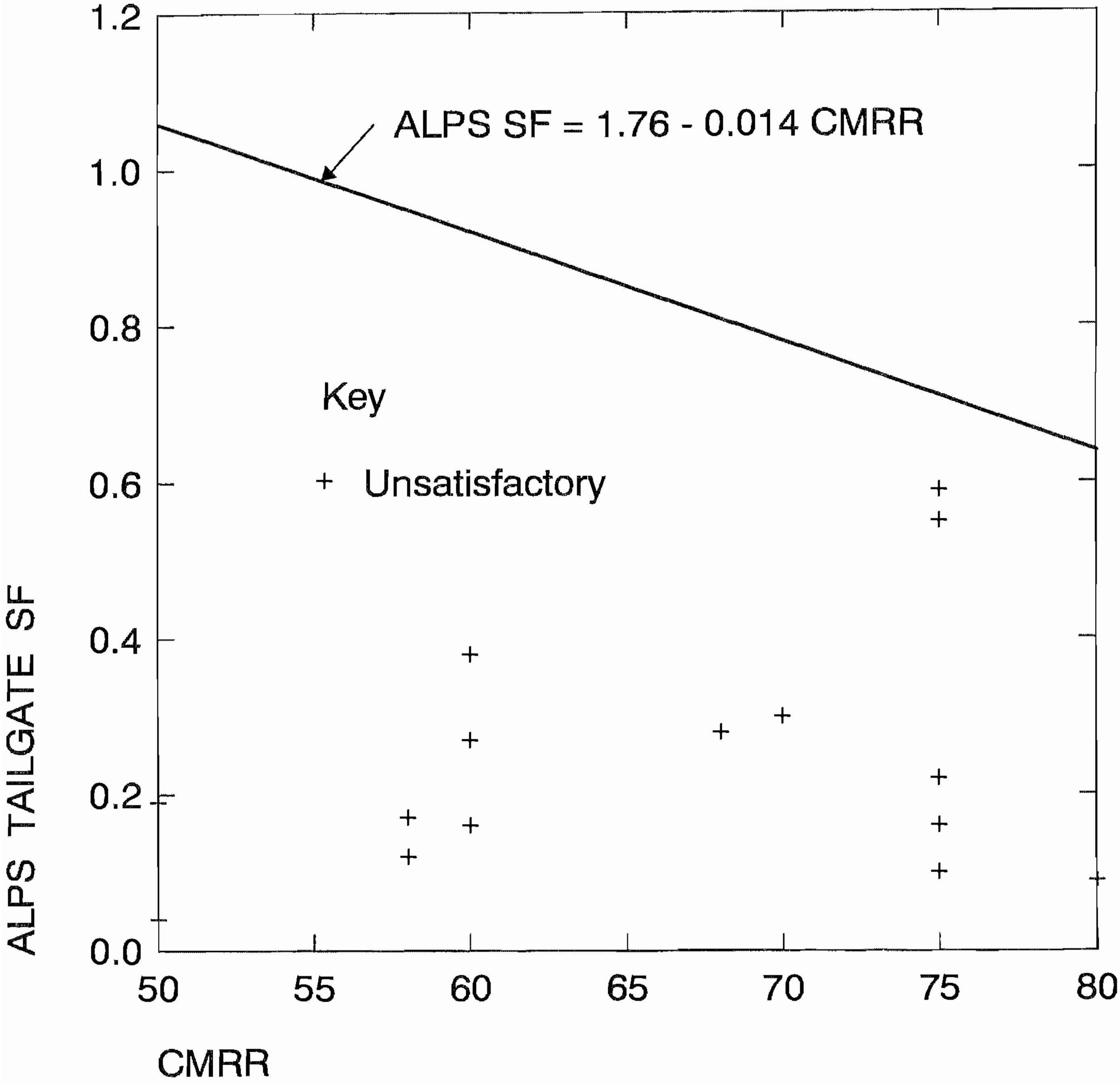

Figure 5. Scatter plot of ALPS tail gate stability factor (SF) versus CMRR for unsatisfactory, large width-height ratio case studies.

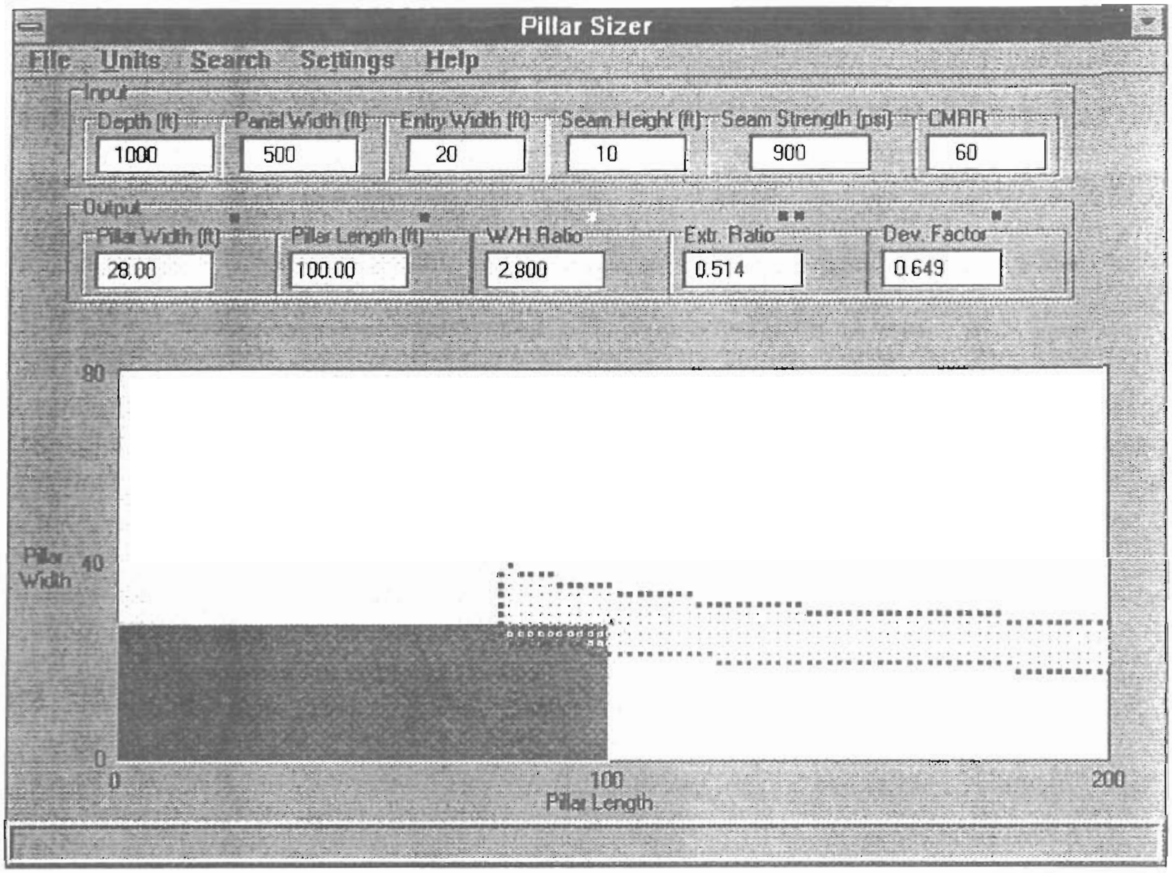

Figure A-1. Pillar Sizer output screen of acceptable yield pillar sizes. Numerical inputs are default values. The numerical outputs correspond to the gray rectangular pillar shown in the lower left corner.

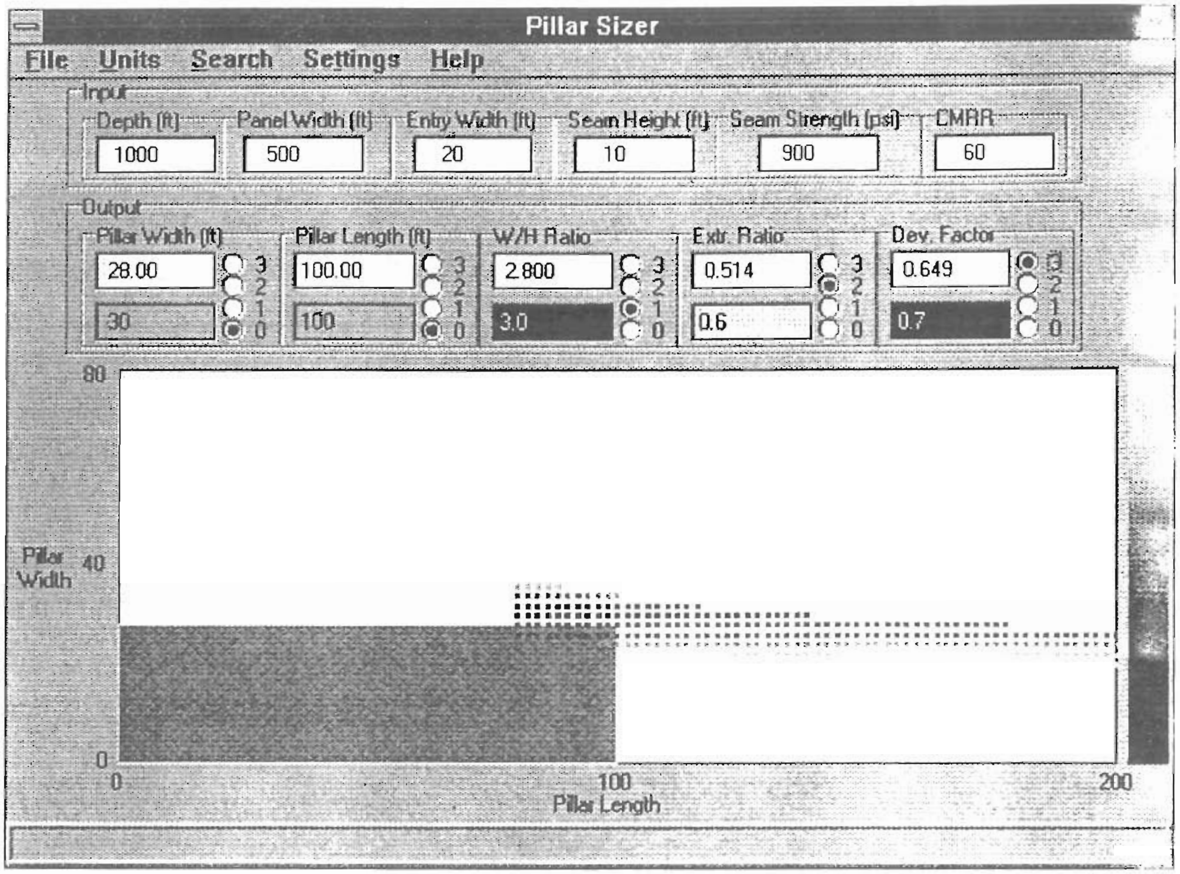

Figure A-2. Pillar Sizer output screen showing optimized pillar sizes based on weighting selected factors. This example assigns a low importance to W/H ratio (button 1), medium importance to extraction ratio (button 2), and high importance to development factor (button 3). The pillar sizes best meeting the criteria match the color at the top of the scale located on the right side of the screen.

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